

GENERAL  ELECTRIC
Research Laboratory
SCHENECTADY, N. Y.

class

2

RECEIVED

MAR 14 1957

ENG. DEPT.

F.C. Vose
Insulator Dept.
Transformer Div.
So. Charles & Cromwell Sts.
General Electric Co.
Baltimore 3, Md.

Dielectrics

GENERAL  ELECTRIC
Research Laboratory

ANALYSIS OF ELECTRODE PHENOMENA IN THE
HIGH-CURRENT ARC

by

J. D. Cobine and E. E. Burger

Report No. 57-RL-1697

February 1957

COMPANY PROPRIETARY

SCHENECTADY, NEW YORK

Reader Please Note

RESEARCH LABORATORY PRACTICE REGARDING
CLASSES OF GENERAL ELECTRIC
TECHNICAL REPORTS

- CLASS 1:** Available to anyone within the limits imposed by Government export regulations. COMPANY BUSINESS INTERESTS ARE NOT INVOLVED. Class 1 reports are listed and abstracted in TIS Briefs.
- CLASS 2:** Generally available to General Electric personnel for use within the Company. COMPANY BUSINESS INTERESTS ARE INVOLVED. Class 2 reports contain information in which the Company has a proprietary interest; hence, the information they contain should not be disseminated outside the Company. In order to make the information generally available within the Company, Class 2 reports are listed and abstracted in TIS Briefs (except in TIS Briefs sent abroad). Additional copies will be supplied to Company personnel on request of Research Information Section.
- CLASS 3:** Not generally available within General Electric. Class 3 reports contain information of a *highly proprietary nature*. SPECIFIC BUSINESS INTERESTS ARE INVOLVED. The distribution is limited to individuals within the Company specifically selected with reference to the subject. Requests for Class 3 reports are cleared with the management of the originating Research Department before being filled. Not listed in TIS Briefs.
- CLASS 4:** Available only to employees personally responsible for the Company's interests in the subject. *Highly proprietary*. SPECIAL BUSINESS INTERESTS ARE INVOLVED. Hence, the distribution is *rigidly limited* within the Company. Class 4 reports are issued in individually numbered copies, which should be returned to Research Information Section when they are not needed. Requests for Class 4 reports are cleared with the management of the originating department before being filled. Not listed in TIS Briefs.

GENERAL ELECTRIC
Research Laboratory

REPORT NO. 57-RL-1697

ANALYSIS OF ELECTRODE PHENOMENA IN THE
HIGH-CURRENT ARC

J. D. Cobine and E. E. Burger

February 1957

Published by
Research Information Section
The Knolls
Schenectady, New York

ABSTRACT

An analysis is made of the phenomena at the electrodes of a high-current short-time arc. It is shown that the input power density to the anode spot is in the range 5×10^4 to 1×10^6 watts/cm². To a first-order approximation, all this power can be carried off by evaporation. Power conducted into the metal and lost by radiation is negligible in the probable operating range. For most materials, the anode spot is probably considerably above the boiling temperature. The process of evaporation holds the spot temperature constant at a value such that the input power and evaporation power are equal. Experimental data indicate that for any given metal the anode spot temperature is that for which the evaporation power density is at least 3×10^5 watts/cm². As an example, for copper the theoretical limits of temperature are 2490° to 3040°K, while experimental data indicate a temperature of 2920°K. Other metals considered are: Ag, Al, C, Fe, Mo, Re, Sn, Ti, W, Zn, and Zr. It is also shown that for the maximum power input that can be expected at the cathode, the thermionic emission current density is very small compared to the observed values of current density. The results are equally applicable to atmospheric pressure arcs and arcs in vacuum.

ANALYSIS OF ELECTRODE PHENOMENA IN THE HIGH-CURRENT ARC

J.D. Cobine and E.E. Burger

INTRODUCTION

This report was first prepared as a Memo Report, P-18, and was later published in part in the Journal of Applied Physics.⁽¹⁾ Since then the authors have expanded the original material and the results have been found of value for both arc interruption studies and for phenomena associated with shock waves. In view of the application of details which have not been published, it was felt desirable to issue the material as a Research Laboratory report.

The phenomena at the anode of an arc are probably relatively simple compared to those at the cathode. There is, however, little in the way of quantitative information that can be readily applied to a wide range of anode materials. This is especially true for arcs at high current and short duration, i. e., thousands of amperes and of the order of 1/120 sec (one-half cycle of 60 cps). In the past it has been rather common to find statements in the literature that the anode is, or probably is, at the boiling point of the material. Llewellyn Jones⁽²⁾ approached the problem of energy balance for sparks by equating circuit stored energy to losses from the electrodes by radiation, conduction, and evaporation. In other studies it is assumed that the anode spot is at the boiling point, and analysis is directed towards expressions representative of the anode drop distribution. Two approaches of this sort have been presented by Finkelburg.⁽³⁾ A related phenomenon is a jet of electrode material emerging from the anode. Finkelburg⁽⁴⁾ has explained these jets for sparks on mercury surface and from the anode of the high-current (several hundred amperes) carbon arc as the vaporization produced by the conversion of the energy of the electrons arriving at the anode. The assumptions are tacitly made that the entire energy input to the anode spot is $J_e (V_a + \phi)$, where J_e is current density of the electron current to the anode, V_a is the anode drop, and ϕ is the work function of the anode surface, and that the energy thus received is all expended in evaporation of metal from the anode surface.

The analysis presented in the present report is aimed at an extension of this approach. It is proposed to evaluate the relative importance of various physical processes occurring at the electrodes of high-current arcs by examining the probable results of each process acting alone. This will involve some idealizing, and the reasonableness of the assumptions may be appraised by examining their consequences. Since this analysis was originally presented in condensed form⁽⁵⁾ additional data from several sources have been examined and found to substantiate the conclusions. It will be shown that for a considerable number of metals the temperature of the anode spot and the erosion loss can be estimated.

ENERGY INPUT

In the following analysis the conditions of a low-pressure arc, characterized by diffuse plasma and a relatively low anode current density, are excluded. The direct electrical power input to the anode surface is equal to the current times the sum of the anode drop and the work function of the surface, the latter term being the heat of condensation of the electrons. It will be convenient to express all quantities on the basis of a unit area of 1 cm^2 . Thus the electrical power input density is

$$P_e = J_a (V_a + \phi) \text{ watts/cm}^2, \quad (1)$$

where J_a is the anode spot current density, V_a is the anode drop, and ϕ is the work function of the surface.

In addition, the anode spot receives thermal and radiant energy from the column immediately in front of it. Part of the thermal energy is carried by the electrons and can be added to the potential component of Eq. (1) as V_T . The power delivered to the anode spot by conversion of the kinetic energy of neutral atoms P_n , and that due to radiant energy from the column P_r , will be taken with P_e to represent the entire energy received by the anode:

$$P_a = J_a (V_a + \phi + V_T) + P_m + P_r \text{ watts/cm}^2. \quad (2)$$

This omits energy received from excited atoms and from the arrival of negative ions, both probably negligible, and resistance heating in the anode.

The only factor in Eq. (2) known with certainty is the work functions. For our purposes it may be taken as 4.5 volts for most metals. The anode drop could be zero, ⁽⁶⁾ might be the least resonance potential of the vapor (1.4 for copper), or as high as the ionization potential (7.68 for copper). For the purpose of analysis, the probable upper limit of V_a will be taken as 7.5 volts, which is reasonably close to the value of the ionization potential of the common metals.

Measured values of anode current density have a considerable range and depend on the anode material. Disregarding early low values, the minimum probable value⁽⁷⁾ appears to be 8000 amp/cm^2 at 100 amperes on steel. Very short-time arcs (less than $100 \mu\text{sec}$) to a tin anode indicated⁽⁸⁾ $10,000 \text{ amp/cm}^2$ at 80 amperes. We have found a value of $30,000 \text{ amp/cm}^2$ for a tungsten-copper anode at 4300 amp lasting $1/100 \text{ sec}$. C.J. Gallagher of this Laboratory has observed anode current densities of at least $50,000 \text{ amp/cm}^2$ for 10-amp arcs on copper. Sparks⁽⁹⁾ of current from 6000 to 18,000 amperes have apparent current densities in the range $60,000$ to $120,000 \text{ amp/cm}^2$. Recently anode current densities at 100 amperes have been reported⁽¹⁰⁾ for a series of metals. The lowest values were for nickel with a range of from $10,000$ - $16,000 \text{ amp/cm}^2$ and the highest for molybdenum, for which it is $51,000$ - $110,000 \text{ amp/cm}^2$. In general, it is probable that the true anode spot current density is greater than the values obtained by measuring the area of the trace left by the arc. This is to be expected because of rapid fluctuations that can possibly take place as they do for the cathode spot.⁽¹¹⁾ For the purposes of our analysis the limits of the anode spot current density will be taken as 8000 and $50,000 \text{ amp/cm}^2$.

The uncertainty involved in the thermal energies of the electrons is not too great. If the commonly accepted gas temperature⁽¹²⁾ of about 6000°K for column of the low-current arc is used, the thermal energy of the electrons in equilibrium with the gas is 0.8 electron volt. However, since it is not firmly established that the electrons are in equilibrium with the gas, the minimum value of V_T will be taken as 1 electron volt, corresponding to an electron temperature of 7730°K . Data are rather limited for high-current short-time arcs. For these arcs, gas temperatures of the order of $12,000^\circ\text{K}$ have been found⁽¹³⁾ for carbon arcs at 250 amperes, and of nearly $16,000^\circ\text{K}$ for 1000 ampere arcs at 2 atmospheres pressure.⁽¹⁴⁾ We shall assume a probable upper limit for the thermal energy of the electrons as 2 volts, corresponding to $15,460^\circ\text{K}$.

The radiant energy from the portion of the column facing the anode spot may be estimated by assuming the column to radiate as a blackbody. In view of the uncertainty, the blackbody values calculated for 6000° and 15,000°K will be used, recognizing that they may be high possibly by a factor of 2 to 10.

The kinetic energy conversion from neutral atom impacts on the surface may be estimated by assuming that not more than one-half, and probably less, of an atom's kinetic energy will be transferred to atoms on the anode surface. At 6000°K the maximum value of this energy is 0.13×10^4 if the atoms are copper. At 15,000°K the gas or vapor is nearly completely ionized so the energy transferred by neutral atom impacts may be neglected. The surface surrounding the anode spot area will also receive energy by radiation and thermal energy transfer from the column. However, because of the slowness of heat conduction through solids, this cannot affect the spot in the short time we are considering.

The probable limits of the various factors are summarized in Table I. These may be considered reasonable values in view of our present knowledge of the very complicated phenomena at the arc spot. In summing up the power input it is assumed that all minima occur together and all maxima occur together, which provides conservative estimates. The lower limit of total input power P_a is about 5×10^4 watts/cm² and the upper limit probably about 10^6 watts/cm². Thus, the input power density to the anode spot involves a little more than an order of magnitude uncertainty. It is evident that the power density is very large, regardless of which limit is taken.

POWER LOSS FROM ANODE SPOT

The energy input to the anode spot must be balanced at that surface primarily by the energy loss by evaporation and by radiation outward from the surface and heat conduction into the metal. The magnitude of each of these components will be determined as functions of surface temperature for a number of metals, for which some experimental arc data are available. The rate of evaporation W is plotted in Fig. 1 for a number of metals and a rather wide range of temperatures by means of the evaporation equation and data found in Dushman's treatise.⁽¹⁵⁾ The evaporation constants used were for the liquid, where available. Since the magnitudes of power density involved are very high, it is necessary to extend the use of these constants beyond the point where they are entirely reliable. However,

TABLE I

Energy Received by Anode Spot

	Minima	Maxima	Units
J_a (anode current density)	8000	50,000	Amp/cm ²
V_a (anode drop)	0	7.5	Volts
ϕ (work function)	4.5	4.5	Volts
T (column temperature)	6000	15,000	°K
V_T (electron thermal energy)	1	2	Volts
$P_e = J_a (V_a + \phi + V_T)$	4.4×10^4	7×10^5	Watts/cm ²
P_n (neutral atom energy)	0.13×10^4	0	Watts/cm ²
P_r (radiant energy density)	0.75×10^4	3×10^5	Watts/cm ²
$P_a = P_e + P_n + P_r$	5.28×10^4	10^6	Watts/cm ²

the uncertainties in these data are much less than those involved in the power input estimates so the procedure is justified. The power represented by the evaporation of metal at the various temperatures is obtained by multiplying the rate of vaporization by the latent heat of vaporization.⁽¹⁶⁾ This involves errors, mostly less than 10 per cent because of the different heat content at temperatures other than the boiling point and because of the variation in specific heat with temperature. The latter factor is not well known at the higher temperatures. The power represented by vaporization is plotted in Fig. 2, and marked by the metal symbol. The upper and lower limits of input power are indicated in Fig. 2 by horizontal dashed lines at 5.28×10^4 and 1×10^6 watts/cm².

The radiation power loss is plotted in Fig. 2 on the assumption that the spot is a blackbody radiator. This assumption gives too high a value for radiation loss since the emissivity will certainly be less than one and probably about 0.3. It is evident from an inspection of the curves of Fig. 2 that the power loss from the surface by radiation even at elevated temperature is far less than the evaporation loss, and may be neglected.

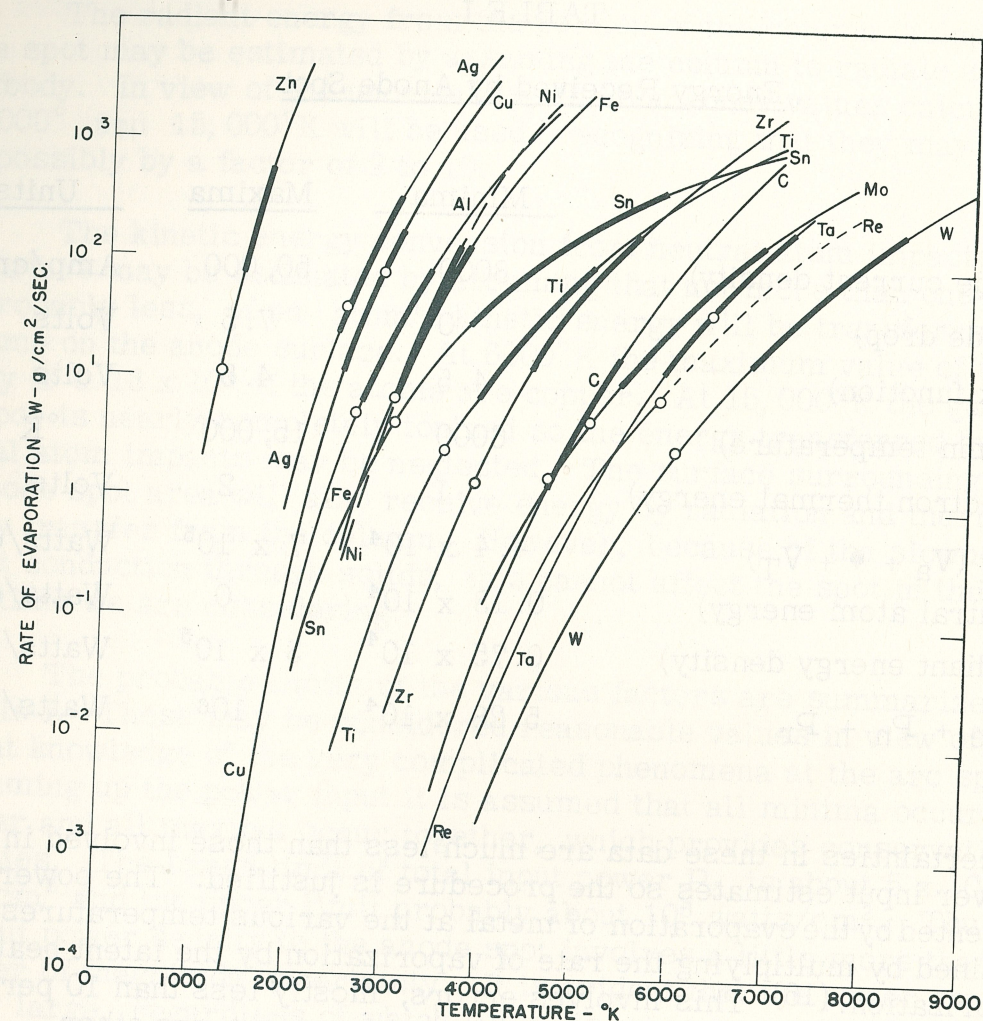


Fig. 1 Evaporation rates for some metals. Circles indicate boiling points; heavy portions indicate probable range at anode spot temperatures.

The assumption will now be made as a first approximation, that all the input power is carried away from the surface by evaporation. For any particular metal the anode spot temperature would be expected to be between the values indicated by the intersection of the evaporation power curve and the input power limits. The amount of heat stored in the metal will be estimated later and shown to be relatively small. From these data, it is seen that for copper the temperature of the anode spot may be found in the range from 2490° to 3040°K. It is interesting to note that the uncertainty in temperature is only

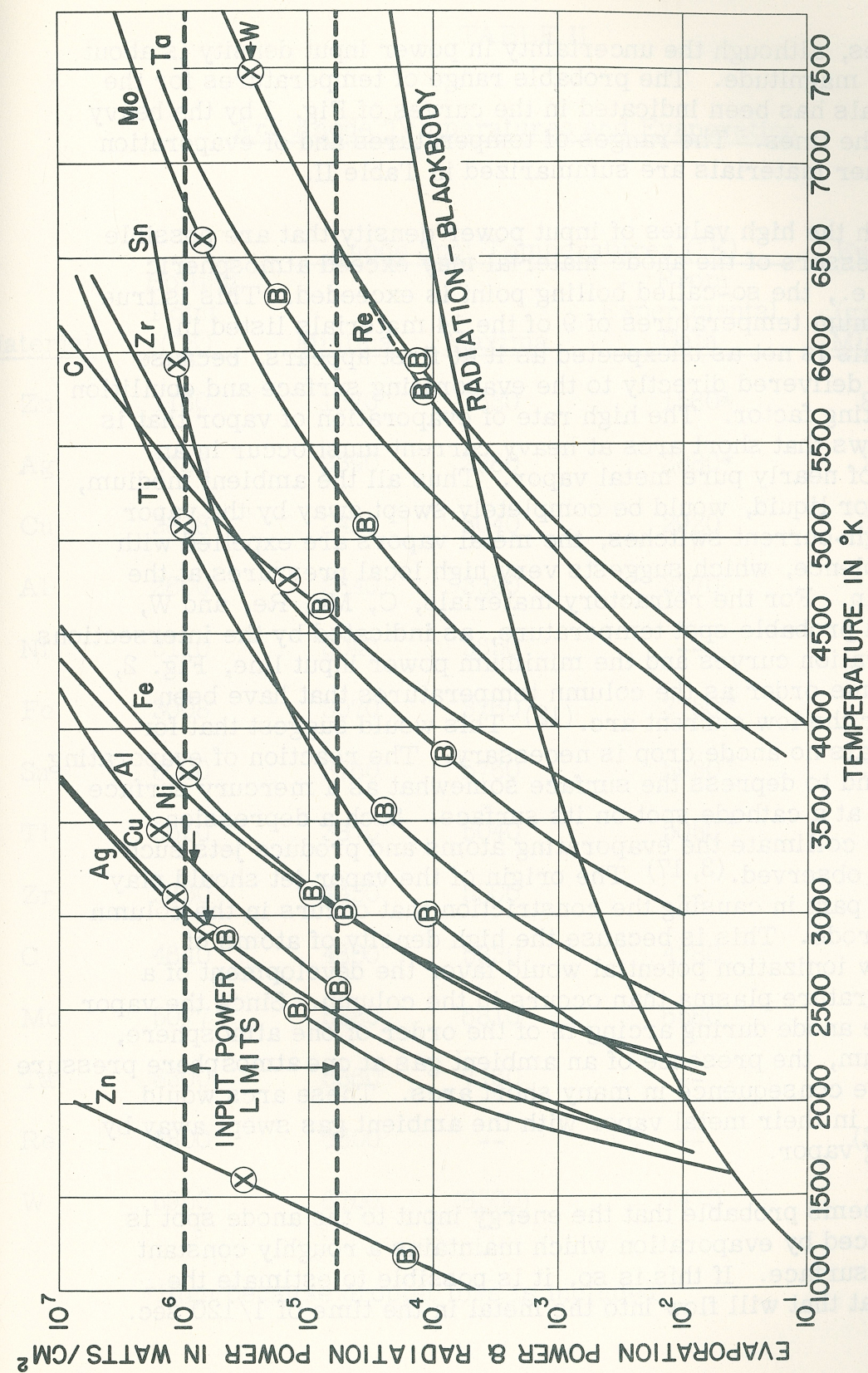


Fig. 2 Balance of power densities for anode spots of arcs. (B) = boiling point, (X) = evaporation power equivalent of experimental erosion, ← = tentative correction of (X) for nonvapor loss.

± 250 degrees, although the uncertainty in power input density is about one order of magnitude. The probable range of temperatures for the various metals has been indicated in the curves of Fig. 1 by the heavy portions of the lines. The ranges of temperatures and of evaporation rates for other materials are summarized in Table II.

With the high values of input power density that are possible the vapor pressure of the anode material may exceed atmospheric pressure, i. e., the so-called boiling point is exceeded. This is true for the minimum temperatures of 9 of the 14 materials listed in Table II. This is not as unexpected as it at first appears, because the power is delivered directly to the evaporating surface and ebullition is not a limiting factor. The high rate of evaporation of vapor that is probable shows that short arcs at heavy current must occur in an atmosphere of nearly pure metal vapor. Thus all the ambient medium, whether gas or liquid, would be completely swept away by the vapor blast. In high-current switches, the metal vapors are expelled with explosive violence, which suggests very high local pressures at the point of origin. For the refractory materials, C, Mo, Re, and W, the minimum probable spot temperature, as indicated by the intersections of the evaporation curves and the minimum power input line, Fig. 2, are of the same order as the column temperatures that have been measured for the low current arc. (12) This would suggest that for these materials no anode drop is necessary. The reaction of evaporating metal will tend to depress the surface somewhat as a mercury surface is depressed at a cathode spot on its surface. Such a depression would help to collimate the evaporating atoms and produce jets such as have been observed. (3, 17) The origin of the vapor jet should play an important part in causing the constriction that occurs in the column at each electrode. This is because the high density of atoms of relatively low ionization potential would favor the development of a higher temperature plasma than occurs in the column. Since the vapor density at the anode during arcing is of the order of one atmosphere, even in vacuum, the presence of an ambient gas at one atmosphere pressure can have little consequence in many short arcs. These arcs would burn entirely in their metal vapor with the ambient gas swept away by the expanding vapor.

It seems probable that the energy input to the anode spot is largely balanced by evaporation which maintains a roughly constant temperature surface. If this is so, it is possible to estimate the amount of heat that will flow into the metal in the time of $1/120$ sec.

TABLE II

Arc Anode Temperatures and Evaporation

Material	Boiling Point (°K)	Anode Spot Temperatures (°K)		From Experimental Data	Evaporation Rate of Vapor (grams/cm ² /sec)	
		Minima	Maxima		Minima	Maxima
Zn	1180	1370	1630	1580*	80	600
Ag	2485	2390	2980	2880*	25	330
Cu	2868	2490	3040	2920	11	180
Al	2600	2640	3320	3270	7	90
Ni	3110	3040	3650	--	9	130
Fe	3008	3070	3760	3750*	9	130
Sn	3000	3760	5760	5930*	30	400
Ti	3550	3870	5040	5050*	8	100
Zr	3850	4430	5500	--	13	200
C	4640	4600	5330	4780	1.4	18
Mo	5077	5380	6810	6580	10	160
Ta	6300	5860	7160	--	15	120
Re	5800	6600	--	--	(30)	--
W	5950	6700	(8300)	7470	16	200

*High because droplet loss is included.

The linear heat flow equation⁽¹⁸⁾ will be used in the calculation for copper to determine an approximate upper limit for penetration of heat in the time under consideration. The linear heat flow equation is:⁽¹⁸⁾

$$\frac{T_s - T}{T_s - T_0} = \text{erf}(\eta x) \quad (3)$$

where

$$\eta = \frac{1}{2\sqrt{\alpha t}}, \quad \alpha = \frac{k}{c_p}, \quad \text{and } T_0 = 300^\circ\text{K}.$$

T_s is the surface temperature and T is the temperature at distance x from the surface. Table II gives data used for our calculations. The use of this equation for the flow of energy into a metal from an anode spot is justified, as it will be shown that the depth of penetration of heat in the time of 1/120 sec is relatively small compared to the diameter of the spot. The calculated temperature distributions for possible surface temperature of 4000°, 3500°, 3000°, 2500°, and 2000°K are shown in Fig. 3 for an elapsed time of 1/120 sec. For a constant surface temperature of 3000°K, i. e., the probable spot temperature, the temperature is above the melting point for a distance of only 0.115 cm. The minimum diameter of spot for a 5000-ampere arc would be 0.36 cm (50,000 amp/cm²) which is roughly three times the melted depth. Thus for currents of this magnitude or greater, the assumption of linear heat flow is justified for time of the order of a half-cycle. The heat of fusion is neglected in the equation, as is the change in the heat conductivity with temperature, so that the actual depth of penetration of melting will be less than that indicated by the curves. The slow rate of heat flow shown here justifies the neglect of heat received from the column by metal outside the active area. In a steady-state arc, however, this source of heat may become quite large.⁽¹⁹⁾

The temperature distribution with depth is shown in Figs. 4 and 5 for Fe, Mo, W, and C. Two curves are shown for each metal, one for the surface temperature corresponding to the minimum power input and the other for the maximum power input. In each of these figures the curve for copper with a surface temperature of 3000°K is shown dotted for reference.

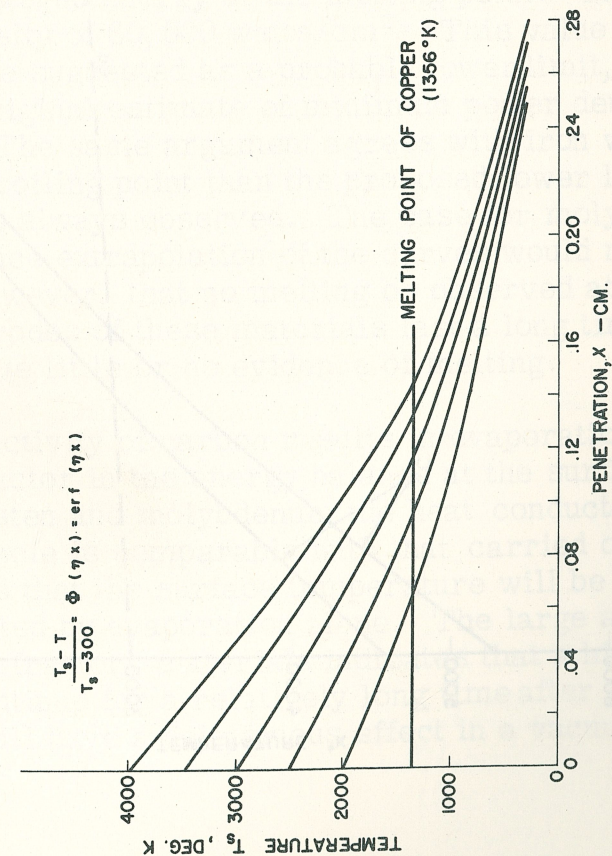


Fig. 3 Linear heat flow from constant temperature surface. Distribution after 1/120 sec.

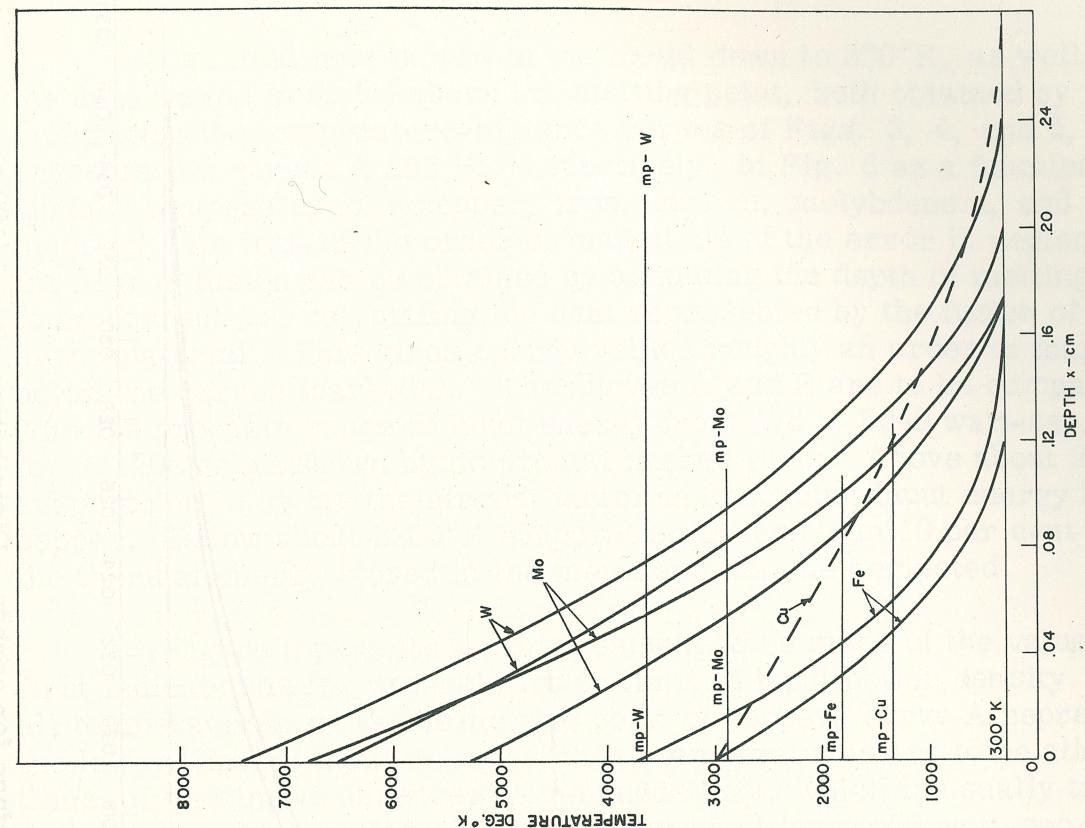


Fig. 4 Linear heat flow from constant temperature surfaces for tungsten, molybdenum and iron. Distribution after 1/120 sec.

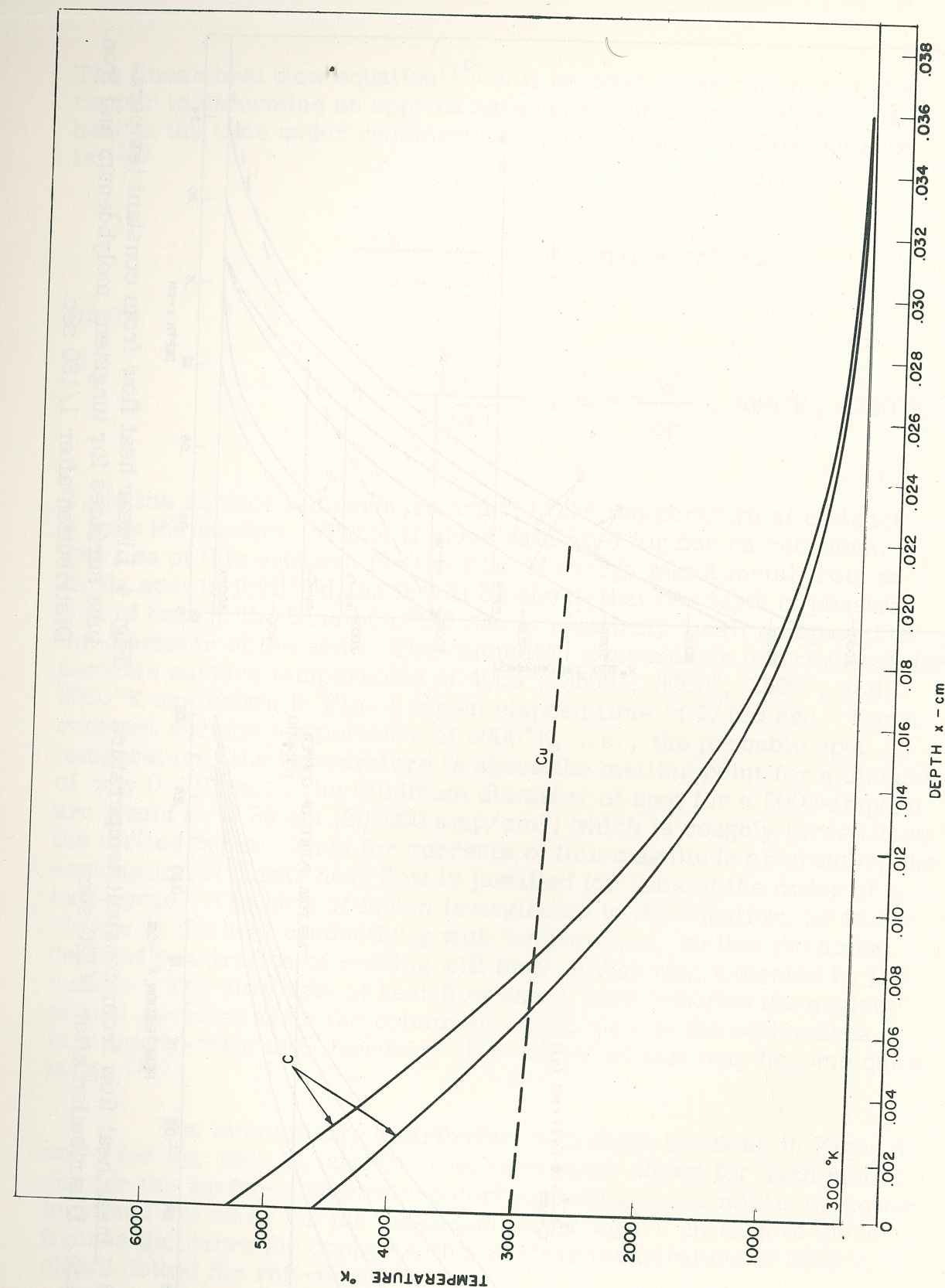


Fig. 5 Linear heat flow from constant temperature surface for carbon. Distribution after 1/120 sec.

The total heat stored in the metal down to 300°K, as well as the heat stored in metal above the melting point, both obtained by integrating the temperature-distance curves of Figs. 3, 4, and 5, are presented as curves A and B, respectively, in Fig. 6 as a function of surface temperature for copper, iron, carbon, molybdenum, and tungsten. An idea of the order of magnitude of the error in neglecting the heat of fusion can be obtained by assuming the depth of melting to be correct and calculating the heat represented by the fusion of this much material. This gives energy values roughly an order of magnitude below the curves marked A. The curves A and B are to be compared with the probable range of input energy from 478 to 8340 watt-sec/cm² for 1/120 sec as shown by horizontal dashed lines. Above about 2700°K evaporation is by far the largest factor in absorbing input energy for copper. Below about 2200°K evaporation is less than 10 per cent of the thermal energy stored in the metal and may be neglected.

Figure 6 permits a reassessment to be made of the value first indicated as the probable lower limit of input power density. For all temperatures above the melting point of copper, curve A represents the lower limit of input energy if these temperatures are to be attained. Thus, if melting is observed at the anode spot, which is usually true, then the input energy for 1/120 sec must be at least 500 watt-sec/cm², i. e., the value of the total stored energy at the melting point. This corresponds to a power density of 60,000 watts/cm². This value is only slightly higher than the value suggested as a probable lower limit, namely, 52,800; thus the original estimate of minimum power density appears quite reasonable. The same argument agrees with iron which requires less energy at its boiling point than the proposed lower limit. In this case also, melting is always observed. The case for molybdenum and tungsten is not clear since extrapolation of the curves would not be justified. It is possible, however, that no melting be observed at low currents. Certainly, electrodes of these materials last a long time at low currents and often give little or no evidence of melting.

The low heat conductivity of carbon results in evaporation being by far the most important factor in the energy balance at the surface. On the other hand, for tungsten and molybdenum the heat conducted into the metal in one-half cycle is comparable with that carried off by evaporation. This shows that the surface temperature will be somewhat lower than indicated by evaporation alone. The large amount of heat absorbed by these refractory materials indicates that a high rate of vaporization will continue for a relatively long time after the current is stopped. This will have a deleterious effect in a vacuum

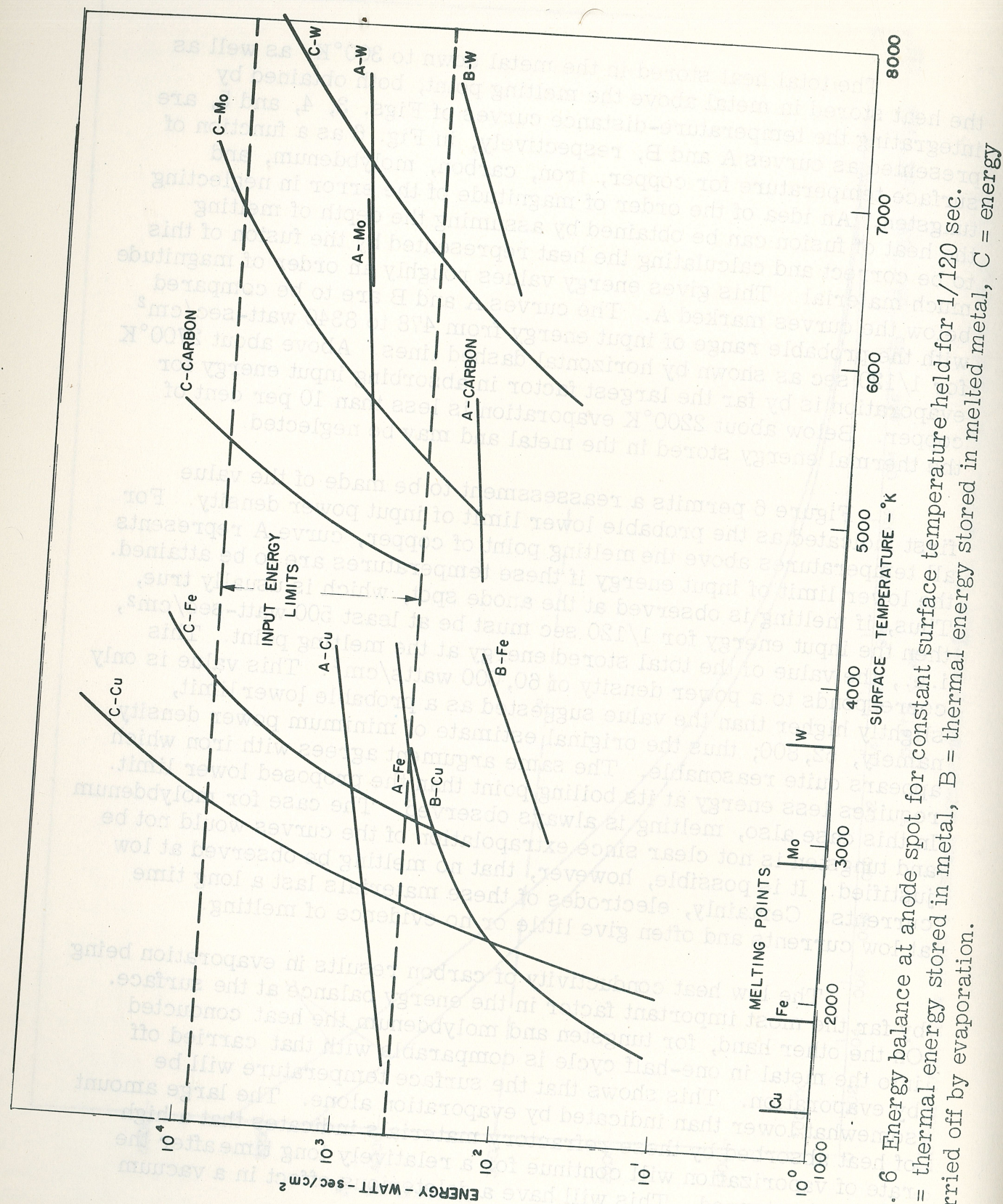


Fig. 6 Energy balance at anode spot for constant surface temperature held for 1/120 sec. A = thermal energy stored in metal, B = thermal energy stored in melted metal, C = energy carried off by evaporation.

switch at high currents. The large amount of thermal energy given to the anode of the refractory materials and their high operating temperature will result in a high thermionic emission from the surface when the polarity reverses. This can produce serious interruption difficulties at high currents.

The initial rate of absorption of heat by a body is quite high. For a spot temperature of 3000°K and copper at 300°K, the rate of heat flow into the surface is: (18) $5520/\sqrt{t}$ watts/cm². At the end of the first μ sec this rate is 5.5×10^6 watts/cm² which is 5.5 times the estimated maximum rate of input at the anode. This shows that for arcs of the order of a microsecond or less duration melting and evaporation may be absent, as has been observed.

The time distributions of temperature for four distances from the surface at the constant temperatures 2500°, 3000°, and 3500°K are shown in Figs. 7, 8, and 9. These figures show the relatively slow initial rate of penetration of heat, whereas Fig. 3 shows the distribution at the end of 1/2-cycle.

In the above analysis, it is tacitly assumed that the molten metal is undisturbed. If it is stirred heat might be transferred faster than by simple conduction. Convective motion of the liquid metal is too slow to be a factor since the maximum distance traveled by a particle under gravitation acceleration in 1/120 sec, neglecting viscosity, is only 0.0339 cm, whereas the depth of melting is about 0.12 cm. It is evident that convective motion in the presence of viscosity in the melted liquid will be very slow and may be neglected.

COOLING PHENOMENA AFTER ZERO CURRENT

An estimation of the amount of heat that can flow out of the solid to maintain evaporation after the arc current has become zero is of considerable interest. A fairly good estimate of the cooling phenomena at the electrode can be made by applying the linear heat flow equation for a solid initially at a uniform temperature T_0 ,

$$T = T_0 \phi(x\eta) \quad (4)$$

T is the temperature at any point (x, t) . The surface at $x = 0$ is suddenly depressed to a temperature of zero degrees Kelvin, i. e., an infinite sink at $t = 0$. This will give an idea of the maximum rate at which energy can flow out of the heated solid. In our case we would

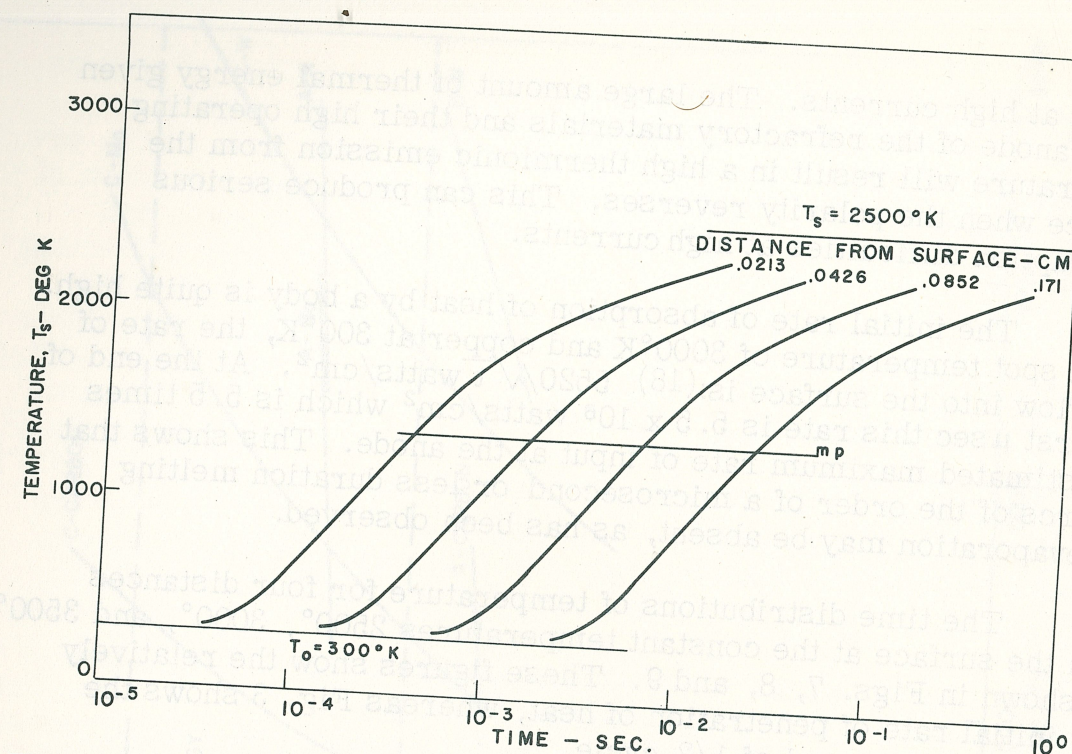


Fig. 7 Linear heat flow from constant temperature surface for copper with $T_s = 2500^\circ\text{K}$.

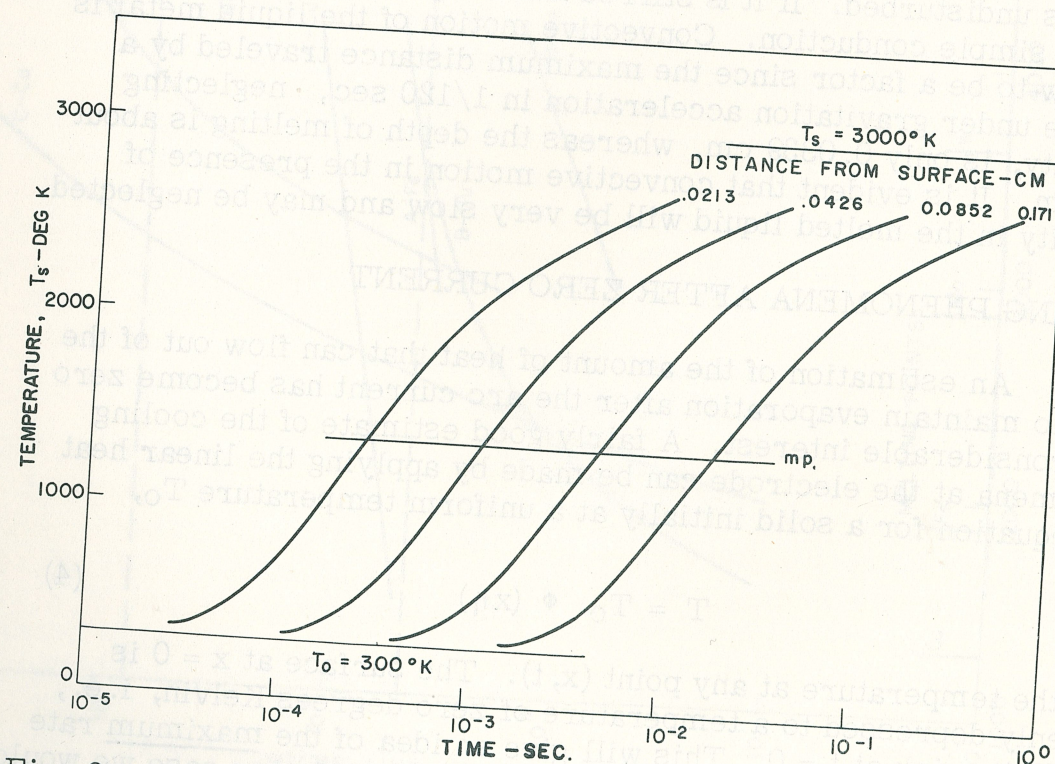


Fig. 8 Linear heat flow from constant temperature surface for copper with $T_s = 3000^\circ\text{K}$.

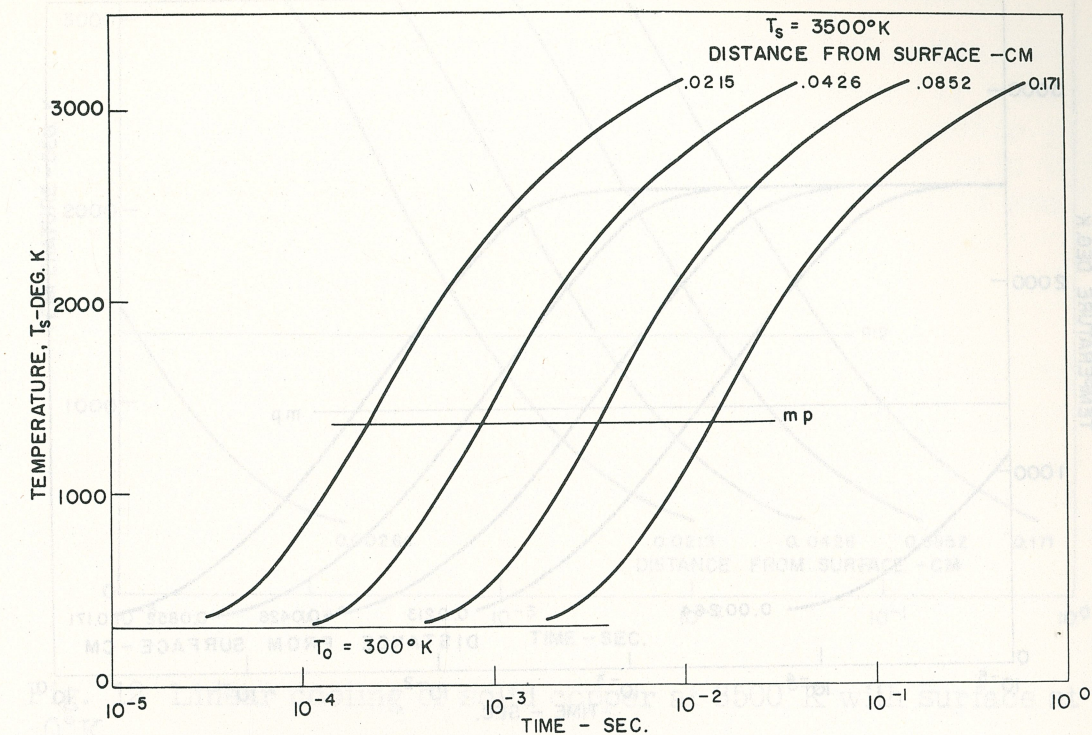


Fig. 9 Linear heat flow from constant temperature surface for copper with $T_s = 3500^\circ\text{K}$.

expect this energy to be dissipated by evaporation, rapidly at first and then more slowly. The results of these calculations are shown in Figs. 10, 11, and 12. These curves show that the rate at which heat flows out is so low that only a depth of about 0.00264 cm contributes much heat to the surface on the first 10 microseconds. Since power system voltage recovery rates are of the order of from 1 to 5 kv/ μs , the rate of residual evaporation must decrease very rapidly if reignition of the arc is to be avoided.

In order to estimate the minimum gas density capable of sustaining an arc, we may refer to phenomena occurring in a large mercury arc rectifier. It is known that in this case an arc cannot be sustained at a vapor pressure less than about 2 microns or a density of 2.65×10^{-6} of that at STP. In order to determine the temperature to which the surface must cool if an arc is not to reignite, some of the equilibrium properties of copper vapor are given in Fig. 13. In this figure W is the rate of evaporation, n_r is the equivalent number of atoms crossing an area of 1 cm^2 in one second, T is the temperature

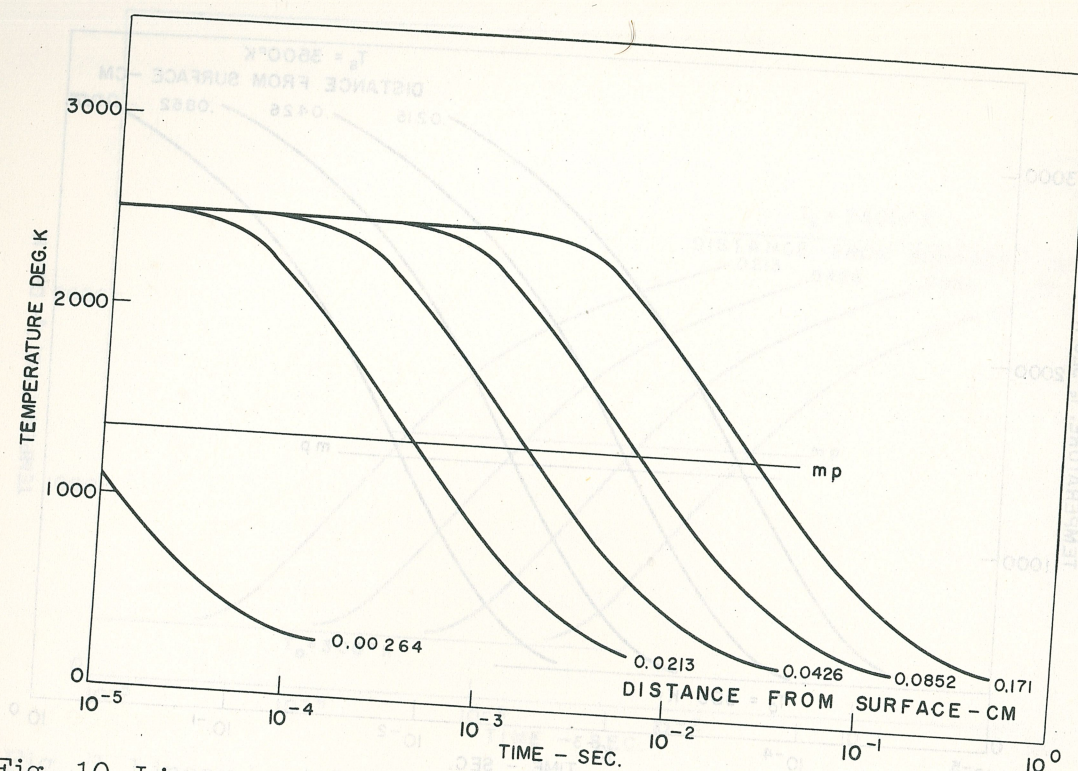


Fig. 10 Linear cooling of solid copper at 2500°K with surface at 0°K.

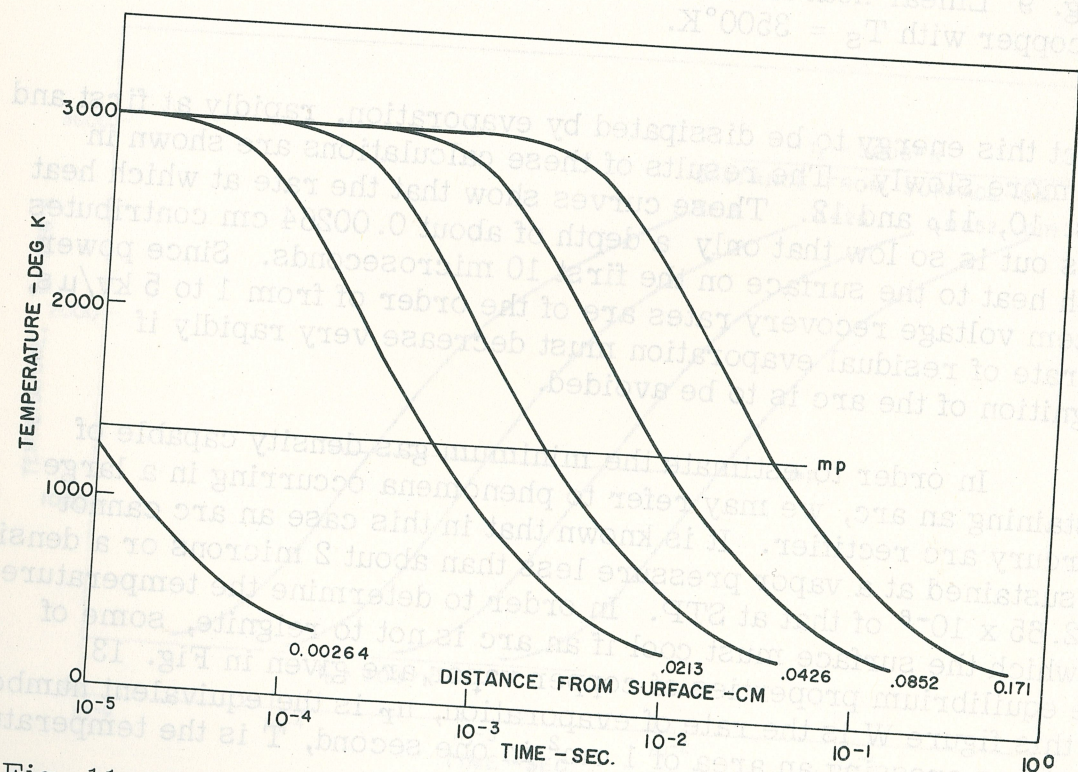


Fig. 11 Linear cooling of solid copper at 3000°K with surface at 0°K.

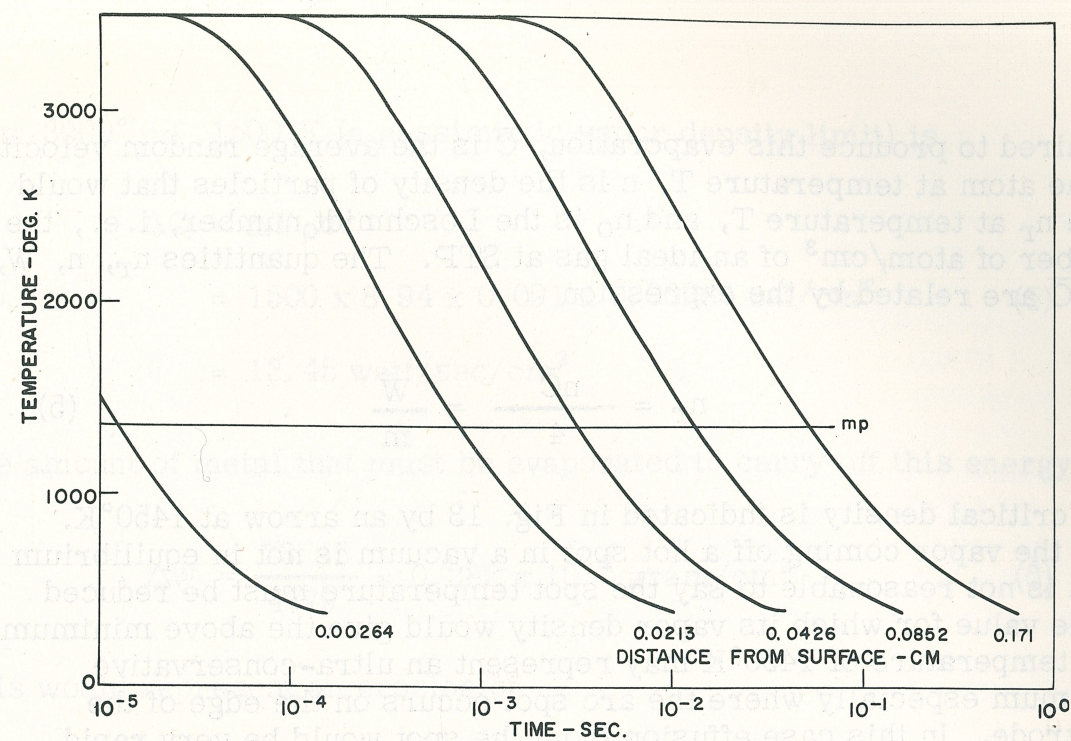


Fig. 12 Linear cooling of solid copper at 3500°K with surface at 0°K.

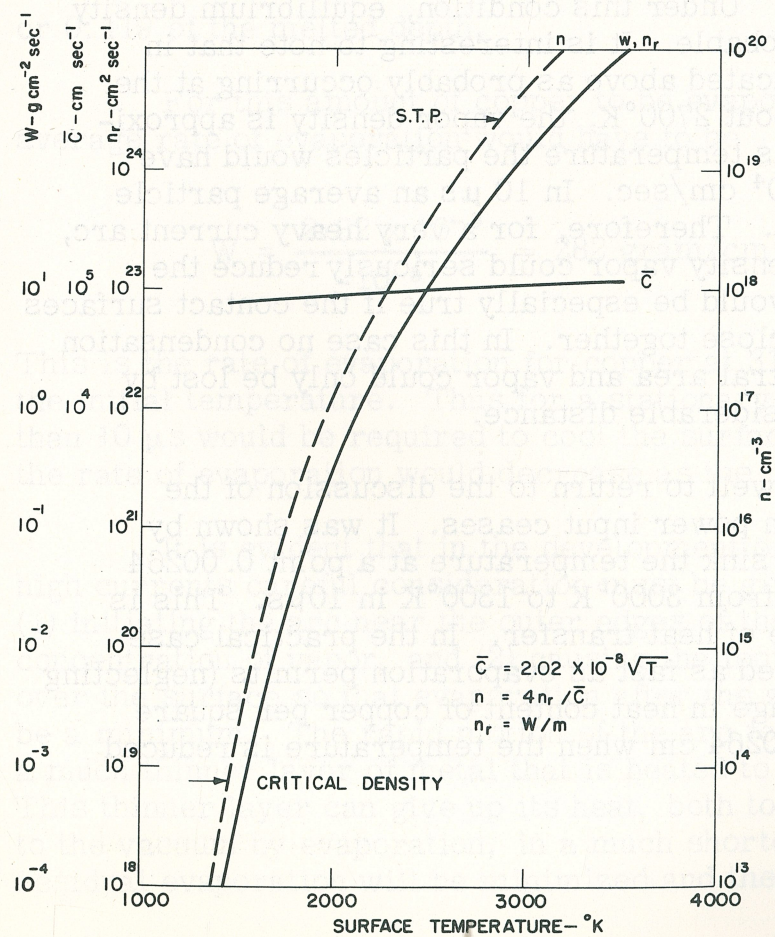


Fig. 13 Equilibrium properties of copper vapor.

required to produce this evaporation, $\bar{C}$ is the average random velocity of the atom at temperature T , n is the density of particles that would have n_r at temperature T , and n_0 is the Loschmidt number, i.e., the number of atom/cm³ of an ideal gas at STP. The quantities n_r , n , W , and $\bar{C}$ are related by the expression

$$n_r = \frac{n\bar{C}}{4} = \frac{W}{m} \quad (5)$$

The critical density is indicated in Fig. 13 by an arrow at 1450°K. Now the vapor coming off a hot spot in a vacuum is not in equilibrium so it is not reasonable to say the spot temperature must be reduced to the value for which its vapor density would give the above minimum. The temperature of 1450°K may represent an ultra-conservative minimum especially where the arc spot occurs on the edge of the electrode. In this case effusion from the spot would be very rapid. However, if the arc occurs at the center of large electrodes the arc spots, if large, "see" only each other. In this case the loss of vapor is confined to effusion from the central cylindrical area, somewhat like a very short fat cigar. Under this condition, equilibrium density would seem much more probable. It is interesting to note that in the temperature range indicated above as probably occurring at the anode for copper, i.e., about 2700°K, the vapor density is approximately that of STP. At this temperature the particles would have rms velocities of 9.45×10^4 cm/sec. In 10 μ s an average particle could only travel 0.945 cm. Therefore, for a very heavy current arc, the large volume of high density vapor could seriously reduce the recovery strength. This would be especially true if the contact surfaces were large and relatively close together. In this case no condensation could take place in the central area and vapor could only be lost by radial diffusion over a considerable distance.

At this point it is well to return to the discussion of the cooling of the hot spot when power input ceases. It was shown by Fig. 11 that for an infinite sink the temperature at a point 0.00264 cm deep would be reduced from 3000°K to 1300°K in 10 μ s. This is the maximum possible rate of heat transfer. In the practical case the heat can only be removed as fast as evaporation permits (neglecting radiation, etc.). The change in heat content of copper per square centimeter for a depth 0.00264 cm when the temperature is reduced

from 3000° to 1500°K (a pessimistic vapor density limit) is

$$\begin{aligned} \Delta Q &= \Delta T \rho_{cv} \\ &= 1500 \times 8.94 \times 0.091 \times 0.00264 \text{ cal/cm}^2 \\ &= 13.45 \text{ watt/sec/cm}^2 \end{aligned} \quad (5)$$

The amount of metal that must be evaporated to carry off this energy is

$$\Delta W = \frac{13.45}{4779} = 0.282 \times 10^{-3} \text{ gram/cm}^2 \quad (6)$$

This would represent an erosion of

$$\Delta x = \frac{2.82 \times 10^{-3}}{8.94} = 3.14 \times 10^{-4} \text{ cm} \quad (7)$$

or 0.119 of the melted depth.

For this amount of copper to be evaporated in 10 μ s the average rate of evaporation would have to be

$$W = \frac{2.82 \times 10^{-3}}{10^{-5}} = 282 \text{ gram/cm}^2 \text{ sec} \quad (8)$$

This is the rate of evaporation for copper at 3170°K, i.e., more than the initial temperature. Thus for a stationary anode spot more time than 10 μ s would be required to cool the surface below 1500°K, since the rate of evaporation would decrease as the temperature decreased.

It is evident that in the development of a vacuum switch for high currents careful consideration must be given to the problems of (1) initiating the arc near the outer edges of the contacts to prevent concentration of vapor, and (2) causing the footpoints to move rapidly over the surface so that evaporation after the zero of current will be a minimum. The rapid motion of the arc footpoints will result in a much thinner layer of metal that is heated to a high temperature. This thinner layer can give up its heat, both to the inner metal, and to the vacuum by evaporation, in a much shorter time. Therefore the residual evaporation will be minimized and the recovery strength increased.

We have observed conditions of very high magnetic field where the arc footpoints apparently reached a maximum velocity and actually ceased continuous motion, leaving a succession of isolated spots with unmarked areas between them. This skipping may result from the probability that the arc footpoints cannot move onto a new area faster than vapor is formed at the surface, and the arc column is bent down parallel to the direction of motion until it makes contact with the electrode at a new point. A similar effect has been observed by others for arcs at atmospheric pressures. (20, 21) A second limitation to the column velocity in the vacuum arc may be that the column cannot move into a zone having an insufficient density of vapor. If this is true the maximum velocity of the column would appear to be not more than a few times the rms velocity of the vapor atoms at the spot temperature.

EXPERIMENTAL DATA

Experimentally determined erosion data can now be used to test the analysis. Erosion data to be suitable for this purpose should be taken at very heavy currents, with the arc burning one-half cycle. Such data were made available to the authors in a private communication through the courtesy of W.R. Wilson and M.A. Guzman.* The erosion from 1/2-inch diameter metal rods, initially separated by 1/32 inch, was measured by them for a single half-cycle of current having a peak value from 11,000 to 26,000 amperes. The present indications are that the loss of material at these currents is about the same for both anode and cathode. The data available consist of the weight lost and the average charge passed in the arc. On the assumption that the entire loss is by evaporation, the following relation permits a check to be made with Fig. 2:

$$P_e = \frac{(m/2) \Delta H 4.18 J}{QM} \text{ watts/cm}^2, \quad (9)$$

where m is the total loss of material in grams from both electrodes for one half-cycle, Q is the average value of the charge passed in coulombs, M is the atomic weight of the material, ΔH is the heat of vaporization⁽¹⁴⁾ in calories per mole measured from room temperature, and J is the anode current density. The current density will

*Both of the Switchgear and Control Division of the Philadelphia Works of the General Electric Company.

be assumed to have an average value of 30,000 amp/cm². The data obtained are plotted in Fig. 2 as the circled X's. The experimental points lie within, or very near, the probable limits obtained from the analysis. Most of the points are rather close to the upper power limit. It is most unlikely that all the erosion is by evaporation for the common metals. Some material is certainly removed by the explosion of gas pockets⁽²²⁾ and some is spattered by the violent motion of the arc footpoints. This would account for the lower values obtained for carbon and tungsten, and the especially high value for aluminum. Preliminary data* aimed at separating vaporization loss from material lost in a spray of droplets, dripping, etc., indicate that this is true. Tentative vapor loss points are shown in Fig. 2 by the horizontal arrows for copper, aluminum and tungsten. Anode spot temperatures derived by assuming that all the loss is by evaporation are summarized in Table II for the various metals. It should be noted that all these temperatures except that for C correspond to evaporation with power densities above 3×10^5 watts/cm² (see Fig. 2). Under steady-state conditions spattering and dripping can be expected to be very large, as it is in welding. For the short-time arcs involved in circuit breakers, dripping at least is small.

CATHODE PHENOMENA

It is not the purpose of this report to examine cathode phenomena in detail. However, some interesting observations appear when the evaporation power is compared with phenomena at the cathode. The cathode mechanism of arcs is very uncertain, but it is possible to set reasonable limits on the energy received by the cathode spot or spots. The principal power density received by the active area of the cathode is that of the positive ions falling through the cathode drop. The cathode spot will lose energy mostly by evaporating electrons, and by evaporating atoms, the latter often erroneously neglected.[†] Thus, for moderately short-time phenomena, at least, we can write

$$J_p V_c = J_e \phi + P, \quad (10)$$

where J_p is the positive ion current density of the cathode, V_c the cathode drop, J_e the cathode spot current density, ϕ is the work function of the metal, and P is the power evaporated at the operating temperatures and is given by the curves of Fig. 2. The ratio J_p/J_e has not been determined. It is possible, as has been proposed,⁽²³⁾

*Courtesy of W.R. Wilson.

[†]For example, L.B. Loeb, Fundamental Processes of Electrical Discharge in Gases, John Wiley and Sons (1939), p. 631.

that the entire current at the cathode could be supplied by positive ions generated in the constricted portion of the column near the cathode. This could be an important mechanism at very high currents. If the entire current were carried by positive ions then an upper limit of the input power would be established. So this assumption will be made. The cathode drop may be taken as 7.5 volts, using copper as an example. The current density of the individual active areas may be taken as 120,000 amp/cm² which was measured⁽²⁴⁾ for small currents. This indicates a maximum input power density of $7.5 \times 102,000 = 900,000$ watts/cm². This input power density could be balanced entirely by evaporation at a spot temperature of 3000°K. At this temperature the thermionic emission current is only 21 amperes/cm² for a work function of 4.5 volts. It would seem from this example that thermionic emission would be extremely unlikely from the low melting point materials. Cathode spot current densities of the order of 1,000,000 amperes/cm² have been observed⁽²⁵⁾ for short-time arcs. If these represent the ultimate value of true cathode current density, the input power density is about 9,000,000 watts/cm². This power input could be balanced by evaporation at 3700°K for which a thermionic current density of 1000 amp/cm² would be obtained. Since the maximum temperatures that could be expected at the cathode spot produces thermionic emission currents negligibly small compared to the observed current density the phenomenon of thermionic emission from most metals except such as tungsten and molybdenum would appear to be unimportant. The presence of both high vapor density and high current density suggests that electron emission by excited atoms could be rather large and also that a rather large proportion of the current could be carried by positive ions as suggested by Weitzel and others.⁽²⁶⁾

The use of tungsten contacts in a vacuum switch would appear to be of questionable value. At low currents very little or no vapor would be developed to sustain an arc and surges would develop due to the sudden stopping of current. This has been observed in our work as well as by others. On the other hand, at high currents thermionic emission would certainly result which, due to the long thermal time constant, would permit the reignition of an arc.

CONCLUSIONS

1. The surface density of input power to the arc anode spot is in the range 5.28×10^4 to 1×10^6 watts/cm². The analysis permits a calculation of anode erosion with considerable certainty.

2. For high-current short-duration arcs, evaporation of metal vapor can account for the major portion of the power input to the anode. Power loss by radiation is negligible in all cases. Heat conduction within the electrode is very much smaller than the evaporation power loss except for the most refractory materials where the two are roughly equal.

3. The anode spot temperature is above the boiling point for most materials. As a consequence, the vaporization rate is high and very high vapor pressures may occur at the anode surface. The expanding high-density vapor will sweep any ambient gas or liquid medium out of the arcing zone, and the arc will burn in pure metal vapor.

4. Thermionic emission from nonrefractory materials appears unimportant as a cathode spot mechanism.

5. For a vacuum switch to clear at the heaviest currents and highest recovery voltages, the arc must be started near the edges of the contacts and kept in motion to minimize residual evaporation.

6. Materials having lowest anode current density and limited evaporation with negligible thermionic emission should be sought.

REFERENCES

1. J.D. Cobine and E.E. Burger, J. Appl. Phys., 26, 895 (1956).
2. F. Llewellyn Jones, Nature, 157, 298 (1946).
3. W. Finkelburg, Hockstromkohlebogen, Springer Verlag, Berlin, (1948).
4. W. Finkelburg, Phys. Rev., 74, 1475 (1948).
5. Gaseous Electronics Conference, Washington, D.C. (October 1953); Phys. Rev., 93, 653 (1954).
6. J.W. Dzimianski and T.B. Jones, Trans. Am. Inst. Elec. Engrs., 54-510.
7. Jones, Kouwenhoven, and Skolnik, Welding J. Research Suppl. (1949).
8. Somerville, Blevin, and Fletcher, Proc. Phys. Soc. (London) B65, 963 (1952).
9. Ware, McCormick, and Sawyer, J. Opt. Soc. Amer., 43, 151 (1953).
10. L.P. Winsor and T.H. Lee, Proc. Am. Inst. Elec. Engrs., Welding Conference (1954).
11. H.V. Bertelle, Brit. J. Appl. Phys., 33, 58 (1952).
12. C.G. Suits, Physics, 6, 315 (1935).
13. K.H. Höcker and W. Finkelburg, Z. Naturforsch., 1, 305 (1946); K.H. Höcker and P. Schulz, Z. Naturforsch., 4a, 266 (1949).
14. D. Th. J. Ter Horst and G.A.W. Rutgers, Physica, 29, 565 (1953).
15. S. Dushman, Vacuum Technique, John Wiley and Sons, Inc., New York (1949), Chapter 11.
16. L. Brewer, Paper No. 3 "Chemistry and Metallurgy of Miscellaneous Materials," Thermodynamics, edited by L.L. Quill, McGraw-Hill Book Company, Inc., New York (1950), IV-19B.
17. W.F. Skeats and C.L. Schuck, Am. Inst. Elec. Engrs., Power Apparatus and Systems, No. 13, p. 848 (August 1954).
18. Ingersoll, Zobel, and Ingersoll, Heat Conduction, McGraw-Hill Book Company, Inc., New York (1948).
19. C.J. Gallagher, Phys. Rev., 79, 231 (1950).
20. W.B. Kouwenhoven and T.B. Jones, Welding J. Supplement (September 1948).
21. L.P. Winsor and T.H. Lee, AIEE Comm. and Elec., No. 21, 143, Paper 56-132 (May 1956).
22. J.D. Fast, Philips Tech. Rev., 10, 28 (1948).
23. Weizel, Rompe, and Schön, Z. Physik, 115, 179 (1940).
24. J.D. Cobine and C.J. Gallagher, Phys. Rev., 74, 1524 (1948).
25. J.D. Froome, Proc. Phys. Soc. (London) 60, 424 (1948).
26. W. Weitzel, R. Rompe, and M. Schön, Zeits. f. Phys., 115, 179 (1940).

DISTRIBUTION

This report, 57-RL-1697, "Analysis of Electrode Phenomena in the High-Current Arc," has been sent out on the following Research Laboratory, General Physics Research Department lists:

Category 10 - Arcs and Discharges

Any inquiries concerning this report should be addressed to:

Miss Beulah Melius
Editorial Services Unit, Room 1A66
Research Laboratory, P. O. Box 1088
Schenectady, New York

SUPPLEMENTARY LIST

Burger, EE	Res. Lab., Rm. 5B24, The Knolls, Schenectady, N.Y.
Casey, R	Circuit Protective Devices Dept., Plainville, Conn.
Charewicz, FJ	Chemical Development Dept., Pittsfield, Mass.
Friedman, H	Res. Lab., Rm. 5B36, The Knolls, Schenectady, N.Y.
Goldberg, LJ	Gen. Eng. Lab., Bldg. 37, Schenectady, N.Y.
Greenwood, A	Laboratories Dept., Philadelphia, Pa.
Larkin, TE	Aircraft Products Dept., Bldg. 28, Schenectady, N.Y.
Lee, TH	Laboratories Dept., Philadelphia, Pa.
Leschen, JG	Met. & Cer. Bldg., Rm. 237, The Knolls, Schenectady, N.Y.
Lucek, J	Chemical Development Dept., Pittsfield, Mass.
Roy, J	Transformer Laboratories Dept., Pittsfield, Mass.
Schneider, H	Laboratories Dept., Philadelphia, Pa.
Skeats, W	Laboratories Dept., Philadelphia, Pa.
Steiner, HC	Power Tube Dept., Bldg. 269, Schenectady, N.Y.
Taylor, RB	Industry Control Dept., Roanoke, Va.
Wellinger, RP	Power Tube Dept., Bldg. 269, Schenectady, N.Y.

TECHNICAL INFORMATION SERIES

Title Page

AUTHOR Cobine, J.D. Burger, E.E.		SUBJECT CLASSIFICATION arcs - arc electrodes		NO. 57-RL-1697 DATE February 1957
TITLE Analysis of Electrode Phenomena in the High-Current Arc 23-6704				
ABSTRACT An analysis is made of the phenomena at the electrodes of a high-current short-time arc. It is shown that the input power density to the anode spot is in the range 5×10^4 to 1×10^6 watts/cm ² . To a first-order approximation, all this power can be carried off by				
G.E. CLASS 2		REPRODUCIBLE COPY FILED AT Research Information Section The Knolls, Schenectady, New York		NO. PAGES 27
evaporation. Power conducted into the metal and lost by radiation is negligible in the probable operating range. For most materials, the anode spot is probably considerably above the boiling temperature. The process of evaporation holds the spot temperature constant at a value such that the input power and evaporation power are equal. Experimental data indicate that for any given metal the anode spot temperature is that for which the evaporation power density is at least 3×10^5 watts/cm². As an example, for copper the theoretical limits of temperature are 2490° to 3040°K, while experimental data indicate a temperature of 2920°K. Other metals considered are: Ag, Al, C, Fe, Mo, Re, Sn, Ti, W, Zn, and Zr. It is also (Abstract continued on following page.)				

By cutting out this rectangle and folding on the center line, the above information can be fitted into a standard card file.

INFORMATION PREPARED FOR:

SECTION: Physical Studies

DEPARTMENT: General Physics Research

Abstract (continued)

shown that for the maximum power input that can be expected at the cathode, the thermionic emission current density is very small compared to the observed values of current density. The results are equally applicable to atmospheric pressure arcs and arcs in vacuum.

Abstract continued on following page.

By cutting out this tab and taping on the back of the above information can be filed in a standard size file.

OFFICE OF
GENERAL PHYSICS RESEARCH
SECTION
INFORMATION PREPARED FOR